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ORIGINAL PAPER

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## Learning elemental structures and dynamic processes in technological systems: a cognitive framework

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**Abstract** An important objective of science and technology education is the development of pupils' capacity for systems thinking. While in science education the term system relates mainly to structures and phenomena in the natural world, technology education focuses on systems designed to fulfill people's needs and desires: examples include systems to control the local environment, or the position or motion of objects. Despite the centrality of the system concept to technology and technology education, issues relating to the teaching and learning of systems within the technology curriculum have been little addressed. This paper explores some elemental structures common to technological feedback control systems, and highlights the relationships between the structural nature and the dynamic behavior of these systems. It is argued that the study of systems and control concepts in technology has the potential to promote higher learning skills such as interdisciplinary thinking and modeling, and an instructional framework for achieving this goal is proposed. Questions and research issues on the fostering of systems thinking in technology education are identified.

**Keywords** Systems · Structure · Dynamic response · Interdisciplinary thinking · Modeling

### Introduction

A driver approaching traffic lights slows down. For safe stopping, multiple variables and factors must be considered simultaneously: the distance from the junction or other cars, the velocity, the acceleration or deceleration of the car, its weight and the road conditions. This is an example of human-machine feedback system in which the driver controls three main variables: distance, velocity—the rate of change of distance with time, and acceleration—the rate of change of velocity with time. Many

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modern cars have systems for cruise control, but so far automatic systems for safe navigation and stopping in road traffic are rare. Why are actions that drivers perform every day so difficult for an automatic system? How are technological systems built and how do they work? Why do systems sometimes get “out of control”? To help people answer such questions, systems and control should form a significant part of technology education.

The terms system and system thinking are broad concepts used to describe and analyze structures and phenomena in natural, artificial and social environments. A system is often defined as an assemblage of inter-related elements, the sum of which exhibits behavior not localized in its constituent parts. That is, “the whole is more than the sum of the parts” (Bertalanffy, 1968). A system can be physical, biological, technological, social or symbolic, or it can be composed of more than one of these. A General Systems Theory (GST) was proposed by Bertalanffy (1968) and others including principles from physics, biology and engineering and later extended into other fields such as philosophy, sociology, organizational theory, management, psychology and economics. The support for the study of systems in science and technology education has been growing over time (Chen & Stroup, 1993; de Vries, 2005; Mayer & Kumano, 1999). In the US, for example, the American Benchmarks for Science Literacy (AAAS, 1993, 1989) stressed that all pupils should learn the concept of a system and develop their understanding of systems as they progress through school. The National Science Education Standards (NRC, 1996) identified systems as a unifying concept that can provide pupils with a “big picture” of scientific ideas as a context for learning scientific concepts and principles. Chen and Stroup (1993) emphasized several strengths of system theory for education: it provides a set of powerful ideas pupils can use to integrate and structure their understanding in the disciplines of physical, life, engineering, and social science; it stresses the complexity of the everyday environment in which the pupil lives; it aims to bridge the gap between the world of the learner and the world of science and technology; and it offers intellectual tools for learners to build an understanding of the dynamic nature of the world. One expression of the centrality of the term system to technology education is that in the Standards for Technological Literacy (ITEA, 2000), published in the US and partly adopted by other countries, the term system appears 521 times, and the term control 99 times. De Vries (2005), in his book on “Philosophy of Technology for Non-philosophers”, examines the relation of the system concept to the four ways of conceptualizing technology as suggested by Mitcham (1994): technology as artefacts, as knowledge, as processes, and as volition. For example, de Vries looks at a system as a type of technological artefact, and points out that engineers can have knowledge of the physical nature of a system or its components, of the functional nature of system, and of the relationship between its physical and functional natures. The distinction between the different purposes of science and technology, as highlighted by de Vries (2005) also helps in understanding the different uses of the term system in the two disciplines. Science aims to develop new knowledge about reality, while technology aims to change that reality according to our needs and desires. Consequently, scientists use the term system mainly in relation to structures and phenomena in the natural world, while technologists and engineers more often relate to systems designed by man for controlling physical variables such as temperature and light, or the motion of objects.

Despite the centrality of the system concept to technology and technology education, issues relating to the teaching and learning of systems within the technology

curriculum have been little addressed. For example: what elemental structures and system dynamic phenomena should be included in the technology curriculum for K-12 education? What are the relevant learning and thinking schemes? Should the acquisition of higher thinking aptitudes be considered a pre-requisite for learning about systems, or an outcome of such learning? In this paper we address these questions by exploring selected examples of technological systems and discuss the related teaching and learning issues affecting conceptual knowledge development. An agenda for further research in these issues is also suggested.

### Elemental structures and dynamic phenomena in systems: the learning experience

A model of a basic dynamic process consisting of input flow, output flow and accumulation with time

The term systems thinking, according to Senge (1990), is concerned with seeing the “whole”, understanding the inter-relationships between system elements and identified patterns of change. At the heart of system thinking in scientific, technological and social contexts is the concept of the change with time of physical or social variables such as the temperature of a mass, the volume of water in a tank or the number of products in a warehouse. Analysis of dynamic processes frequently relates the instantaneous value of a specific variable, its rate of change (derivative) or accumulation (integral) with time. For a moving body, for example, the instantaneous velocity  $v(t)$  (m/s) expresses the rate of change of distance  $x(t)$  (m) with time; Mathematically, the distance  $x(t)$  is the integration of the velocity  $v(t)$  with time. Another example is the filling of a tank, as illustrated Fig. 1; in this system, the rate of change of volume  $v(t)$  ( $\text{m}^3$ ) of water in the tank is determined by the difference between the input flow  $q_{\text{in}}(t)$  ( $\text{m}^3/\text{s}$ ) and the output flow  $q_{\text{out}}(t)$  ( $\text{m}^3/\text{s}$ ), as expressed in Eqs. 1, 2. Many people intuitively grasp the behavior of systems characterized by a constant rate of change. When that rate of change itself varies with time, it becomes much more difficult to understand.

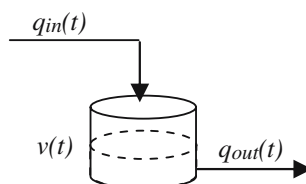
The “net” flow into the tank

$$q(t) = q_{\text{in}}(t) - q_{\text{out}}(t) = \frac{dv(t)}{dt} \quad (\text{m}^3/\text{s}). \quad (1)$$

The volume of water

$$v(t) = \int (q_{\text{in}}(t) - q_{\text{out}}(t)) dt \quad (\text{m}^3). \quad (2)$$

**Fig. 1** Volume and flow of water in a tank



For example, Booth-Sweeny and Sterman (2000), who call the case of filling a tank mentioned above as the “bathtub dynamics”, examined to what extent highly educated pupils could draw a graph of the change of the volume  $v(t)$  in time for different cases of input/output flows. Among subjects having a strong background in mathematics and science, about 77% succeeded in solving this task for a periodical high/low change (square-wave pattern) of the input flow  $q_{in}(t)$ ; only 48% drew a correct graph of change of volume  $v(t)$  with time for a continuous increase and then sharp fall of the input flow  $q_{in}(t)$ , (saw-tooth pattern). The output flow  $q_{out}(t)$  was defined as constant for both cases. This example demonstrates peoples’ difficulties in understanding dynamic phenomena with variables that change with time.

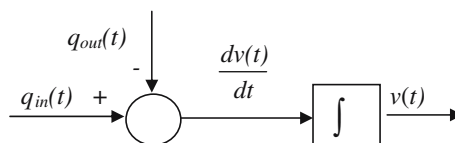
As mentioned earlier, the case of filling a tank is just one example of a range of elementary systems characterized by input flow, output flow and accumulation effects. Therefore it is helpful to draw a general model as illustrated in Fig. 2. In this model, the dependent variable  $v(t)$  can be, for instance, the number of people in a hall or the number products in a store. This model demonstrates two important points concerning this elemental system: first, the rate of change of the observed variable depends on the difference between the input flow and the output flow; second, the output of the process is the result of the accumulation (integration) effect.

The model in Fig. 2 differs from that of the system in Fig. 1 in that it presents separately the differentiation between the input flow and the output flow and the accumulation effect. Here we focus on a specific model, but later we will discuss in more detail the issue of using models and modeling in studying systems.

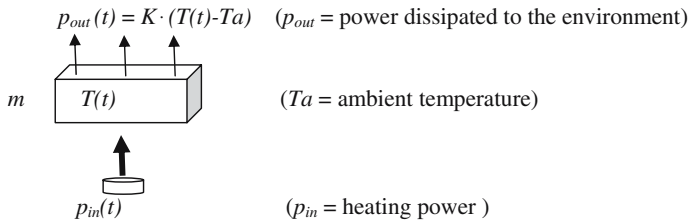
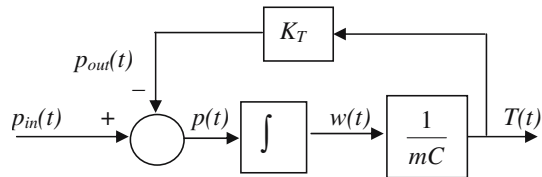
### A dynamic processes characterized by natural balance

A common case in systems is when either the input or output flow depends naturally on the existing value of the observed variable. In filling a balloon, for example, the flow of air into the balloon decreases when the pressure in the balloon increases. Systems of this type tend to reach a natural balance. In heating an object of mass  $m$ , as seen in Fig. 3, the input flow is the power  $p_{in}(t)$  (W) of the heating source; the output flow  $p_{out}(t)$  (W) is the power dissipated to the environment.

The model for the heating process, as presented in Fig. 4, is based on the equations developed in the Appendix. For this process, the net power  $p(t) = p_{in}(t) - p_{out}(t)$  determines the rate of temperature change; the heating energy  $w(t)$  is the integral of the net power  $p(t)$ . When the temperature  $T(t)$  of the body rises, the power  $p_{out}(t)$  dissipated to the environment rises as well, and therefore the rate of increase in the temperature declines. The temperature  $T(t)$  stabilizes when the loss of power  $p_{out}(t)$  to the ambient equals the heating power  $p_{in}(t)$ . This is a typical case in which the observed variable changes exponentially with time.



**Fig. 2** A functional model of tank

**Fig. 3** Heating a body**Fig. 4** A model for the processes of heating a body

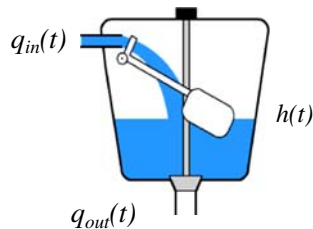
Dynamic phenomena of an exponential nature are found in many natural and technological systems; examples include the change of current in a resistor–capacitor electric circuit and the diffusion of material from an area of high to an area with lower concentration in biological cells. In all of these cases the rate of change of the observed variable decreases with time, although in some cases this is a result of a decrease in an internal “potential gap” rather than an output flow.

Understanding dynamic phenomena in systems at such a conceptual level is difficult for most learners. Harrison and Treagust (2000), in their effort to suggest a typology of school science models, claim that the most complex and abstract models are concept–process models, which are process thinking models for understanding and applying important concepts such as physical and chemical equilibrium or current flow in network systems. de Kleer and Brown (1983) also point out that novice learners often face difficulties in understanding the physical or functional nature of a given system, or building a mental model for a given system. Therefore, asking inexperienced learners to draw a model for a system new to them is obviously unrealistic. The use of mathematics to analyze this type of process depends on pupils’ prior knowledge, but a mathematical approach does not necessarily promise better understanding and is not a substitute for qualitative analysis.

### Impact of man-made feedback

In the case of a heated body, as demonstrated above, the system is likely to balance naturally. However many technological systems consist of man-made negative feedback aimed at stabilizing a specific variable or a set of variables. The flush cistern is one of the most frequent examples in textbooks on feedback control. Figure 5 illustrates this system. The required level (reference) of the water in the cistern is determined mechanically, commonly at the factory or during installation. The ball-cock detects the actual level of the water and decreases the input flow as the level approaches the desired value.

The structure of this system and its operating principle are simple and understood by many people. However, to explore the dynamic process characterizing this



**Fig. 5** A flush cistern

system, and see how it compares to other feedback control systems, we show its block diagram in Fig. 6.

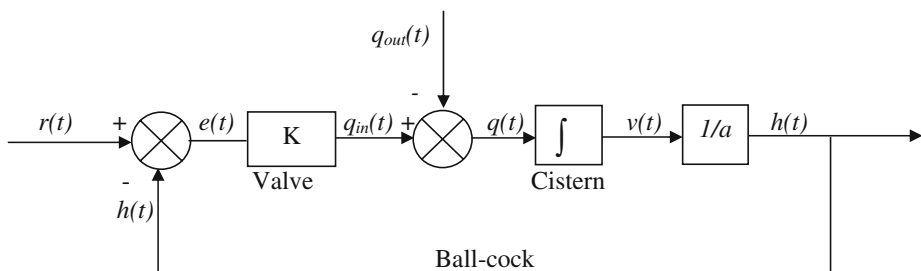
The model for this system is compound because the system has at the same time an internal feedback and an output flow. In Fig. 6, the constant  $K$  expresses the ratio between the input flow  $q_{in}(t)$  and the error  $e(t)$  between the required level  $r(t)$  and the actual level  $h(t)$ , as given in Eqs. 3, 4

$$e(t) = r(t) - h(t) \quad (\text{m}) \quad (3)$$

$$q_{in}(t) = K \cdot (r(t) - h(t)) \quad (\text{m}^3/\text{s}). \quad (4)$$

The model describes a linear relation between the input flow  $q_{in}(t)$  and the level of the water  $h(t)$ . Since in practice the ball-cock moves rotationally, trigonometric analysis is required to express the correct relation of input flow  $q_{in}(t)$  to the actual level  $h(t)$ . Assuming a linear relation between variables, or in other words linearization, as in this case, is just one example of reducing complexity in modeling complex systems. This approach is useful for conceptual discussion, as common in science education; in teaching technology, the difference between the simplified model and the nature of the real-life system needs greater emphasis. Pupils who construct a robot should learn, for example, that friction and backlash in a mechanical transmission cannot be ignored because these factors can significantly influence their robot performance. This is just one example of the different role of models in teaching science or teaching technology (de Vries, 2005; Gilbert, 2004; Harrison & Treagust, 2000).

It is apparent that the functional block-diagram of the flush cistern in Fig. 6 is formal and not easy to draw. Yet, through exposing pupils to block diagrams of this type they can learn to



**Fig. 6** Block diagram of the control system in a flush cistern

- identify basic variables in a system, such as input, output, feedback and distortion,
- explore dynamic phenomena in a system,
- distinguish between dynamic analysis and steady-state analysis, and
- recognize the difference between the real system and the model.

This example demonstrates that modeling a system is often more complicated than drawing a mechanical diagram or an electrical schematic for it. There is a need to clarify the objectives of introducing such subjects into the curriculum, to research the standard of K-12 pupils capable of grasping these issues and to find the best instructional approach. Some of these points are raised in the discussion section in this paper.

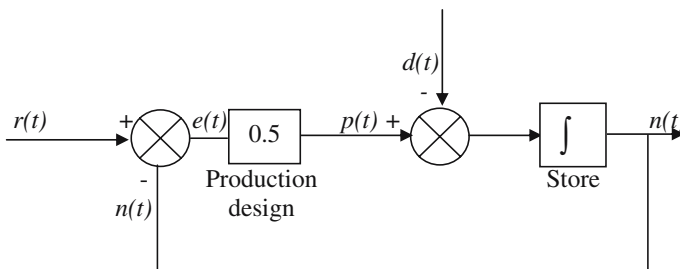
### An example of a dynamic process in an organizational context

System thinking is often presented as a broad term related to systems in natural, artificial, social or economic contexts. To explore such a functional similarity, let us consider a dynamic process in a factory that produces bottles and stores them in a warehouse. It is given that the rate of bottle production  $p(t)$  (bottles per day) is determined by the difference between the required (reference) number of the bottles in the store  $r(t)$ , and the actual number of bottles  $n(t)$ . If the production coefficient is  $K = 0.5$ , for example, every day the factory produces 50% of the shortfall in the warehouse on that day. The rate of bottle demand  $d(t)$  (bottles per day) depends on the customers, and therefore is unknown. Equations 5, 6 demonstrate this case

$$p(t) = K \cdot (r(t) - n(t)) \quad (\text{bottles/day}) \quad (5)$$

$$\frac{dn(t)}{dt} = p(t) - d(t) = K \cdot (r(t) - n(t)) - d(t) \quad (\text{bottles/day}). \quad (6)$$

A block diagram for this system, as seen in Fig. 7, indicates the analogy between this case and the flush cistern. When the number  $n(t)$  of products in the store increases the rate of production  $p(t)$  decreases, and thus the process is of an exponential nature. In the case of constant demand rate  $d(t)$  the systems stabilizes at a constant production rate  $p(t) = d(t)$ ; despite the feedback, there will be a constant error  $e(t)$  between the desired value  $r(t)$  and the actual stock  $n(t)$ .



**Fig. 7** A model for a production system

## A numerical model

It is useful to apply a discrete analysis to this bottle-production system in which a decision on the production rate takes place once a day. Consider a case:  $r = 1,000$  (desired value),  $K = 0.5$  (production coefficient), and  $d(t) = 0$  (no demand for bottles).

- Initially the store is empty with a daily production of 500 bottles in the first day.
- The second day begins with 500 bottles in store, a shortage of 500 bottles; the production that day is 250 bottles.
- On the third day with 750 bottles in the store production is cut to 125 bottles. Thus the store fills exponentially, with the filling rate (production) decreasing as the number of products accumulated approaches the desired value. This kind of discrete analysis can be easily executed in a spread sheet, as seen in Table 1, Fig. 8. After studying the basic model, pupils can easily alter it and see the results. For instance, if a constant demand of  $d = 200$  (bottles/day) appears, this change can be entered into the model by adding  $-200$  to the term for the number of bottles  $n(t)$ , and the results displayed numerically and graphically. It must be admitted, however, that only meager literature exists on how pupils manipulate or understand numerical models of the type discussed above, or on their ability to grasp the analogy between the diverse examples we have seen so far in our discussion.

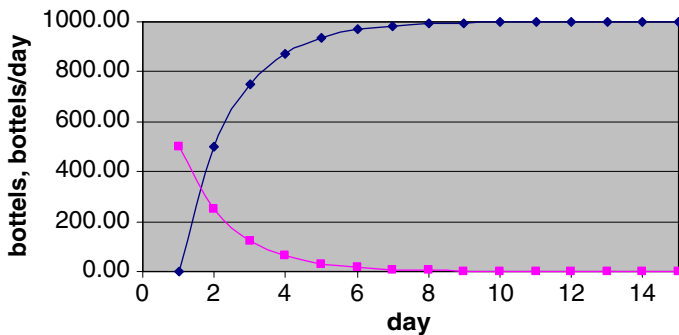
## Understanding oscillations in a feedback system

The problem of instability and oscillations is undoubtedly a central issue in understanding the physical and functional nature of systems. Many scientists, engineers and teachers of science and technology use the example of oscillations of a mass and spring to explain the phenomena of oscillations in a system. In feedback control, however, this analogy does not always fit and can rather lead to misconceptions. For

**Table 1** The change of bottles in the store according to the formula:  $p(t) = (1,000 - n(t)) * 0.5$ ,  $n(t) = n(t - 1) + p(t - 1)$

$t$ (day)	$n$ (bottles)	$p$ (bottles)
1	0.00	500.00
2	500.00	250.00
3	750.00	125.00
4	875.00	62.50
5	937.50	31.25
6	968.75	15.63
7	984.38	7.81
8	992.19	3.91
9	996.09	1.95
10	998.05	0.98
11	999.02	0.49
12	999.51	0.24
13	999.76	0.12
14	999.88	0.06
15	999.94	0.03





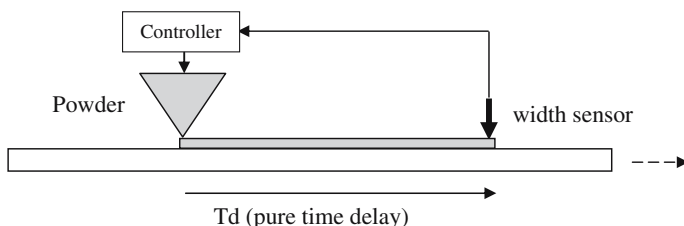
**Fig. 8** The change in time of the number of bottles in the store and the production rate for a case of no demand

instance, one reason for oscillations in feedback systems is the presence of a pure time delay in the control loop, as seen in system in Fig. 9.

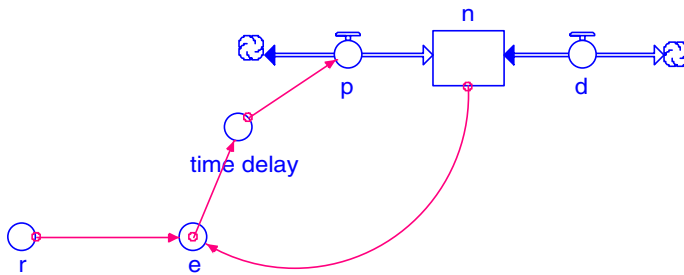
Figure 9 represents a system in which an object moving from left to right is coated with a thin layer of another material. If the sensor that measures the coating thickness is placed at a distance from the coating point, there is a time delay  $T_d$  before the data on the measured coating reaches the sensor. A similar delay exists, for instance, when hot water reaches a tap from a distant boiler. In management systems, time delays might appear because of slow decision making or the time required to change a production line. In the bottle production system which we have met earlier, a time delay can be introduced into the model by adding a delay of  $T_d$  days between decision and implementation of a new production rate  $p(t)$ . Figure 10 shows a model for this system in the STELLA simulation environment.

Selected delays of 2 days and 4 days, as seen in Fig. 11, are enough to illustrate the problem. For a 2 day delay in the system, the number of items in the store exceeds 1,500 units, and stabilizes at the desired value ( $n = 1,000$ ) only after several fluctuations. For a delay of 4 days in the closed loop, the production rate is getting out of control. It should be noticed that the simulation indicates a negative value for the number of stored items and for the production rate, which is of course unrealistic. The model can be improved by limiting variables  $n$ ,  $p$  to positive values only. Studying examples of this type can demonstrate to pupils the similarities and differences in both structure and function of systems in diverse environments.

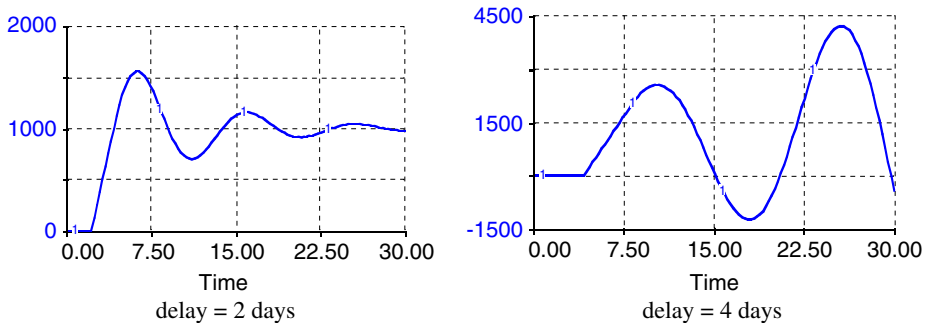
So far we have looked at some elemental structures and dynamic phenomena in technological systems. Additional issues that might be discussed include positive feedback, feed-forward control, non-linear effects and multi input–output systems. Studying these concepts involves a high level of abstraction by the pupils, and there



**Fig. 9** An example for pure time delay in a feedback control system



**Fig. 10** Simulation model of the system for bottle production with time delay in the control loop using STELLA software



**Fig. 11** Response of the system for bottle production with a delay in the feedback loop

is a need for a careful examination of the cognitive aspects of teaching and learning this subject in K-12 education. Such a discussion follows.

### Cognitive aspects of teaching–learning about technological systems

It is argued that through exploring technological systems pupils can learn to:

- recognize the relationship between the physical nature and the functional nature of a system;
- assess and represent dynamic phenomena in natural, technological and social environments both textually and graphically;
- identify relationships of quantity, rate of change or integration between variables;
- recognize desirable or undesirable processes caused by feedback in a system; and
- learn about the differences between a model of a system and its actual structure and properties.

There are skills already taught within science and technology curricula which allow pupils to develop an understanding of systems. These skills include interpreting graphs, creating graphs from data, using a wide range of qualitative and quantitative data and applying mathematics to describe and analyze dynamic phenomena or to characterize system properties. The following paragraphs consider the thinking schemes used in learning this subject.

## Interdisciplinary thinking

The notion of imparting general thinking competencies such as system thinking is based on a hidden belief about pupils' ability to transfer knowledge and thinking skills from one subject to another (Bransford, Brown, & Cocking, 1999). Although teachers of science and technology are frequently aware that some of the concepts they teach are not restricted to their own subject, they rarely consider comparable scientific, technological or social examples from other disciplines. For example, the exponential changes of a variable with time, or harmonic oscillations, occur in physics, biology, chemistry, environmental processes, earth sciences, electronic circuits, control systems and economic management. However, teachers seldom generalize these concepts, for a variety of reasons such as lack of knowledge, confidence or teaching time or worry about confusing the pupils or overloading them. Educators sometimes hope that pupils will transfer knowledge or thinking skills from a specific subject to other contexts or from school to daily lives and the workplace. Yet the educational literature shows that transfer of knowledge or thinking schemes is limited, and occurs only between closely related subjects or to previously studied situations (Perkins & Salomon, 1988). Teachers need to make explicit the general principles behind particular knowledge and skills, and to encourage pupils to make their own generalizations, a process Perkins and Salomon (1998) called "bridging". The distinction between deductive and inductive learning style is useful in discussing how to foster system thinking in a technological context (Felder & Silverman, 1988; Wankat & Oreovicz, 1993). Inductive reasoning starts with specific examples and then proceeds to induce generalization. Deductive reasoning, on the other hand, starts with a general principle and then deduces the consequences in specific cases. The inductive reasoning process is the natural way to construct a knowledge structure in a new area, and is therefore the common way of teaching–learning in science and technology. Deductive reasoning requires that the individual be in a formal operational stage, in Piaget's (Inhelder & Piaget, 1958) terms. The educational literature (Doyle & Lunetta, 1978; Driver, 1978; Krajcik & Haney, 1987) however, shows that many learners, including pupils at high school or college freshmen are covert operational thinkers. For these pupils, the learning of concepts in technological systems must progress in small steps, making the transition to formal reasoning a slow process that takes place through learning experiences that are context-specific. Rather than seeing the possession of formal thinking abilities as a prerequisite for learning general system concepts, educators have to see the study of the physical and functional nature of systems as a framework for helping pupils to develop their formal thinking abilities. To create meaningful learning, instruction has to help pupils connect new ideas to what they already know, construct their own new knowledge and apply their existing knowledge to new situations and contexts. Since many students, including high achievers who major in science at technology at high school, are at the concrete operational or transitional stages towards formal thinking, learning should use familiar examples to facilitate learning more complex ideas; a limited number of basic concepts should be studied from different perspectives and throughout numerous intensive experiences.

## Using analogies

Learning interdisciplinary concepts in science and technology is often based on analogies, namely taking an example from one field to clarify a phenomenon in

another. Using the flow of water in a pipe to explain direct electrical current in a circuit, or using oscillations of a mass-spring system to explain oscillations in a coil-capacitor circuit are just two typical teaching examples of analogies. Yet, analogies are usually restricted to the subject being taught: a new concept in physics is linked to other known physical phenomena; familiar biological examples are invoked to explain a new area of biology and so on. Generalization over other scientific, technological or social areas is rarely attempted for lack of subject-matter knowledge or confidence. Gentner and Holyoak (1997) point out that analogy is a powerful cognitive mechanism that people use to make inferences and learn new abstractions or to understand a novel situation in terms of one that is already familiar. In the course of reasoning by analogy, the novel or unfamiliar topic is viewed as another example of a familiar concept. Although relying on prior knowledge seems to be a natural way of learning, people often fail to recall relevant examples, or to take advantage of their prior knowledge in learning a new subject (Gick & Holyoak, 1980). Novice learners, in particular, may have difficulties in transferring knowledge and thinking skills to a new context. Gentner, Loewenstein, and Thompson (2003) suggest the “analogical encoding” approach, in which analogies are not just a means of building new concepts from prior knowledge, but also allow concrete cases from different disciplines to focus learners on precisely those aspects that generalize across cases. New concepts and general ideas about systems behavior can be learned through examples and analogies related to pupils prior general knowledge, specific cases or principles studied in the technology and science curriculum, or new knowledge and principles learned initially through comparison of examples from diverse areas.

### Contextual learning

There is little benefit in teaching pupils symbols that are detached from their real-world referents, because these symbols often have no meaning for the pupils (Resnick, 1987). Dewey (1916) advocated a curriculum and a teaching methodology tied to the child’s experiences and interests, and to the physical and social contexts in which learning takes place. Theories of situated cognition (Brown, Collins, & Duguid, 1989) contend that knowledge is inseparable from the contexts and activities within which it develops. According to contextual learning theory, learning occurs only when learners process new information or knowledge in such a way that it makes sense to them in their own frames of reference, their own inner worlds of memory, experience, and response. Since concepts are internalized through the process of discovering, reinforcing, and relating to real life situations, it is essential for the learner to discover meaningful relationships between abstract ideas and practical applications. Building upon this understanding, the teaching of dynamic processes in systems should be applied to as many different environments and forms of experience as possible, whether in school or out of it.

### Using models and modeling

Using models and modeling is a fundamental part of learning science and technology (de Vries, 2005; Gilbert, 2004; Grosslight, Unger, Jay, & Smith, 1991; Harrison & Treagust, 2000; Jackson, Krajcik, & Soloway, 2000; Schwarz, 2005). A model of a system is a set of representations, rules, or reasoning structures that help to analyze,

predict or explain the system's behavior in different situations. Building a physical model of a system, drawing a block diagram, writing mathematical equations or constructing a computer simulation for a system are just a few examples of modeling. As we have seen earlier in this paper, describing a system by a model is often a difficult task. McCormick (2004) discusses the flush cistern example with its control of water level by the ball-cock. He establishes that it is obvious to individuals and easy to explain. Drawing a diagram for this system is more difficult: technologists set this task will probably produce quite different versions. Another example is the system for temperature control by a thermostat. Explaining how a thermostat works or drawing an electrical schematic for a circuit containing a thermostat is simpler than presenting a block diagram or a functional model for this system. The dilemma is that systems thinking or system modeling aims to reduce complexity, not increase it. These examples demonstrate that modeling is often difficult and must be learned gradually and be well exercised. In this regard, it is worth mentioning Gilbert's (2004) suggestion to involve pupils in using models and modeling in four stages: (a) learning to work with given models, (b) learning to revise models, (c) learning the reconstruction of a model, and (d) learning to construct models. This author stresses that the construction of a model *de novo* involves perceiving the emergence of properties of the complete model from those of the components of the model; he also points out that "exemplar sequences to take pupils through these four stages for particular models/phenomena have yet to be developed" (p. 122).

### Learning through "hands on"

Teaching an interdisciplinary topic such as systems presents educators with a challenge: how to make pupils participate actively in the learning process and to avoid the trap of basing learning mainly on delivery by the teacher. Learning theories, such as Constructivism (Papert, 1991; Piaget, 1957), Situated Learning (Lave, 1988) and Cognitive Apprenticeship (Brown et al., 1989), stress that learning and doing are inseparable. Hands-on and self-directed activities oriented towards design and discovery are powerful ways for learning and for developing cognitive skills. Active learning is best achieved through instructional approaches such as project-based learning, problem-based learning, inquiry-based learning or design-based learning, which engage pupils in activities such as planning, decision-making, problem solving and developing, presenting and reflecting on the learning process. This learning often ends with a product created by learners such as a physical model of a system. Such pupils' products should be relevant to the learners and suitable for sharing with others (Bereiter & Scardamalia, 1987). Technology education, more than other school curricula, provides a natural framework for applying such a learning approach because in technology studies pupils often aim at building a working system rather than just a conceptual model. Hands-on robotics, for example, fits well the constructivist view of learning. The problem is that educators often see this type of schooling as "back door learning" (Marian & Blaine, 2004), and rarely link pupils' project work to learning formal concepts in systems and control, or encourage pupils to gain epistemological knowledge of the technological issues they are engaged in. Another way of hands-on learning is to let pupils operate, investigate and manipulate ready-made modular control systems in the school laboratory. For example, Barak (1990) has explored the impacts of using of an instructional system for

computerized light control to teach pupils concepts such as feedback control, measurements and data conversion.

### Using simulation

Certainly, one of the major tools for teaching and learning about system structure and functioning is computer simulation. In the last 30 years, a wide literature (Forrester, 1968; Sterman, 1994) and variety of simulation packages relating specifically to system dynamics have been developed both for instruction and for professional use. Examples include: STELLA Powersim. Vensim, Model-it or GoldSim. Using simulation in the teaching and learning of system dynamics has several educational advantages, providing opportunities to (Spector, 2000):

- analyze systems of different types or degrees of complexity;
- formulate and test hypotheses;
- explore dynamic phenomena that are difficult to follow in real conditions, for example very slow or very fast phenomena;
- examine models or conditions that cannot be physically created;
- rapidly repeat analysis of dynamic processes with stochastic variables.

Simulation offers considerable benefits in the analysis of system dynamic processes, but is not a substitute for hands-on work in the laboratory: pupils need to work with physical components and instrumentation. Educators are increasingly aware that the mere using of computers in class does not promise deeper learning. For example, Barak (2004) has found that the extensive use of simulation in studying electronics can remove pupils from the real world of technology and mask superficial learning.

### Teachers' role

Stressing the importance of pupils' activities in the learning process does not make what teachers are doing less important. Spector (2000) suggests the notion of "gradual complexity" as an effective way to promote constructivist learning. First, traditional tutorial and expository instruction establish a foundation on which to build meaningful activities. Only later are learners provided with open-ended tasks, with an exploratory or experimental approach and gradually diminishing tutor guidance. Bransford et al. (1999) and Richardson (2003) also point out that a common misconception regarding constructivist theory is that teachers should never tell pupils anything directly, but, instead, should allow them to construct their knowledge for themselves. Constructivism is a theory of learning, not a pedagogy of teaching. A teacher's subject-matter knowledge and involvement in pupils learning is a critical factor in creating a successful learning environment.

### Conclusion and research agenda

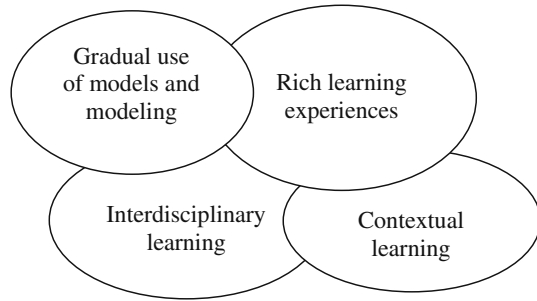
This paper has highlighted a range of elemental systems and dynamic phenomena in technological systems, which are also relevant to natural, artificial and social contexts, and which underlie the study of system thinking in an interdisciplinary approach. Several cognitive aspects of the study of system structure and function,

especially dynamic processes in feedback systems, have been discussed. To conclude, we suggest a cognitive-based instructional framework for fusing the study of system thinking into a technology curriculum embodying the following four themes:

- *Contextual learning.* It is widely agreed that connecting subject-matter studied at school to pupils' real world situations and their daily lives is a major factor in fostering learning and developing pupils intellectual skills. The teaching of system concepts and control in technological, scientific and social contexts offers a natural framework for contextualizing learning, because individuals experience such systems everywhere and are affected by them. Educators, however, need to adapt the learning program to pupils' age, scholastic background, interests and physical and social environments.
- *Deliberate instruction of interdisciplinary concepts.* To enhance pupils understanding of general concepts such as feedback, stability, errors, exponential responses or oscillations, educators need to engage pupils in learning these phenomena in areas such as technology, physics, biology, or management. Pupils' learning should relate directly to the similarities or differences in the appearance of the phenomena in diverse contexts, situations and environments, and to the advantages and limits in generalizing concepts across diverse disciplines.
- *Gradual development of modeling abilities.* In engineering and science there is now a diverse range of modeling tools for visual, graphical and mathematical representations and analysis of systems structure and behavior. This is a major resource for developing, organizing, and presenting technological and scientific knowledge. The process by which people learn to use models or to build their own models is a relatively unresolved issue in the psychological and educational literature. It is then important that the application of models to the teaching and learning of system structure and dynamics should be carried out very carefully, given that the ability to set up models of real-world systems and to use these models for analyzing systems dynamic behavior is usually the province of experienced technologists. Beginners in a field must learn first to work with existing models and then to modify them before trying to build original models for unfamiliar systems. Such study should not be based on a single modeling approach but should rather seek to expose learners to diverse methods for modeling and analysis.
- *Rich learning experiences.* To learn interdisciplinary concepts in systems and control, pupils need to go through a variety of learning experiences beyond a teacher's presentation or simulations. Problem-based learning or project-based learning that includes the design and construction of physical working systems or models provides a promising platform for fostering active learning about systems, provided that these learning activities are tied to a theoretical framework. For such learning, school laboratories should include rich and flexible instrumentation such as control system modules that pupils can experiment with, as well as standard educational modular sets of building blocks that pupils can use to design and construct their own systems.

The four themes of the model in Fig. 12 are shown partially overlapping to stress that this model must be seen as a whole rather than as discrete approaches or methods.

**Fig. 12** An instructional framework for fostering system thinking in technology education



Pursuing the ideas and questions outlined in this paper, an agenda for further research on pupils' learning of concepts of systems and control is suggested:

- further inquiry into pupils' understanding of the structural and functional nature of systems, and the relationships between system structure and its dynamic behavior,
- investigation of pupils' abilities to generalize concepts learned over multiple technological, scientific and social domains,
- research into pupils' understanding of technological–scientific models and the factors affecting learners abilities to work with models and modeling, and
- research on the ways to link effectively the learning of theoretical concepts in systems and control with working on technological projects and problem solving.

## Appendix

### Analysis of temperature change in a heating an object

Consider a heat source supplying power  $p_{in}(t)$  to an object of a mass  $m$ , as seen in Fig. 3. As the object's temperature exceeds the temperature environment temperature, the body loses power  $p_{out}(t)$  to the environment. The output flow is proportional to the difference between the body's temperature  $T(t)$  and the ambient temperature  $T_a$  and to the heat conductivity  $K_T$  (W/°C). These relationships are presented by Eqs. 7–10.

The heating energy

$$w(t) = m \cdot C \cdot dT(t) \quad (C). \quad (7)$$

The heating power

$$p(t) = \frac{dW(t)}{dt} = m \cdot C \frac{dT(t)}{dt} \quad (W) \quad (8)$$

$$p(t) = p_{in}(t) - p_{out}(t) \quad (W). \quad (9)$$

The power dissipated to the environment



$$p_{\text{out}}(t) = K_T \cdot (T(t) - T_a) \quad (\text{W}). \quad (10)$$

To simplify, we choose  $T_a = 0$ . The rate of change of an object's temperature is determined by the “net” heating power  $p(t) = p_{\text{in}}(t) - p_{\text{out}}(t)$ . Accordingly

$$m \cdot C \frac{dT(t)}{dt} = p_{\text{in}}(t) - p_{\text{out}}(t) \quad (\text{C}) \quad (11)$$

$$m \cdot C \frac{dT(t)}{dt} = p_{\text{in}}(t) - K_T \cdot T(t) \quad (\text{W}). \quad (12)$$

This is a differential equation of the first order. One can see from the equation itself (without writing the solution of  $T(t)$ ) that as the temperature  $T(t)$  increases, the rate of change of the temperature  $dT(t)/dt$  decreases. This is the basic characteristic of an exponential response. The equation also indicates that for the case of a constant input power  $p_{\text{in}}$ , the temperature stops changing ( $dT(t)/dt = 0$ ) when the output power  $p_{\text{out}}$  lost to the ambient is equal to the input power  $p_{\text{in}}$ . Therefore, the steady-state temperature can be calculated as shown in Eqs. 13, 14

$$p_{\text{in}} - K_T \cdot T_{\infty} = 0 \quad (\text{W}) \quad (13)$$

$$T_{\infty} = \frac{1}{K_T} p_{\text{in}} \quad \text{C}. \quad (14)$$

The block diagram for this system is shown in Fig. 4.

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